

Roles and needs for simulation for the development of new reactors

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The Generation IV International Forum has adopted 4 primary goals for new nuclear energy systems

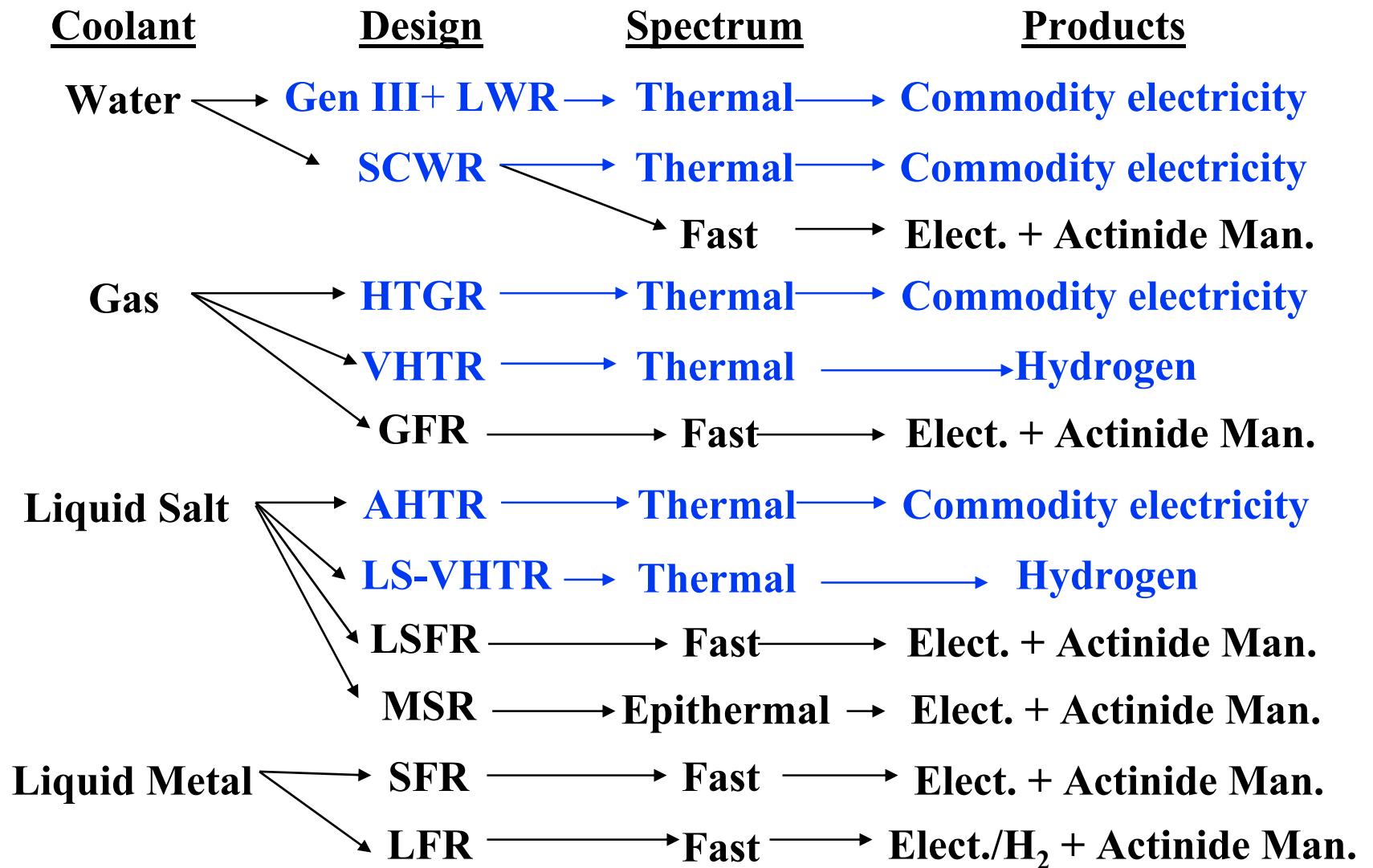
- **Economics**
 - Major drivers: reactor capital costs (scale economies), operational reliability, additional products (hydrogen/actinide management)
 - Second-order drivers: fuel-cycle, O&M and FOAKE costs
- **Proliferation Resistance and Physical Protection**
 - Proliferation resistance through global system configuration (centralization of fuel cycle services) and advanced safeguards
 - Physical protection through increased intrinsic barriers to theft, hardening of safety systems (passive safety), optimization of facility physical configuration
- **Sustainability**
 - Improved waste management (efficient use of limited repository space), efficient use of resources
- **Safety and Reliability**
 - Improved, flexible safety analysis (CSAU, PIRT)
 - Optimized reactor operation and maintenance

Key simulation goal: Enable the design, licensing, deployment and reliable operation of new nuclear infrastructure that advances these goals

Modern computation and simulation methods provide the key tools to further reduce nuclear energy costs

- **Reactor design**
 - Modern approach for Code Scaling, Applicability, and Uncertainty Analysis (CSAU) for reactor safety analysis and licensing for normal operation, transients and accidents (safety licensing)
 - Predictive tools to understand and improve reactor system reliability (investment protection)
 - Computer aided design and manufacturing (capital cost)
 - » Integrated 3-D models with P&ID and equipment lists, automate change management, 3-D time/motion studies
 - » Finite element analysis thermal/seismic/mechanical response of structures (rapid thermal transients/high seismic loading/ extreme external events)
 - » Automated manufacturing
 - Codes for physical security system design and optimization (security licensing)
- **Reactor Operation and Maintenance**
 - Databases and project management tools for all aspects of operations and maintenance
 - Focus on achieving high system reliability and capacity factor

A taxonomy of reactor design options

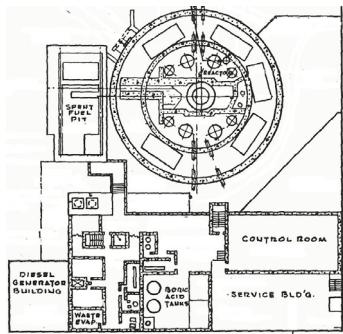
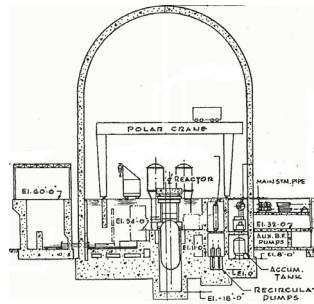


Examples discussed here are thermal reactors

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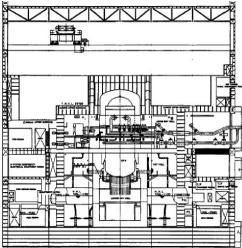
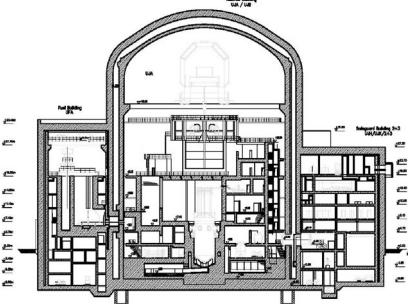
Economics will be strongly influenced by design optimization to increase power while reducing structures/equipment

Gen II

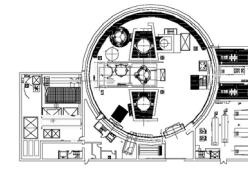
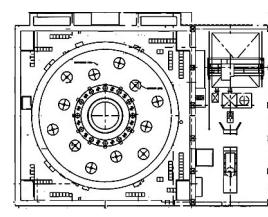
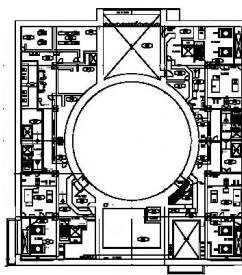
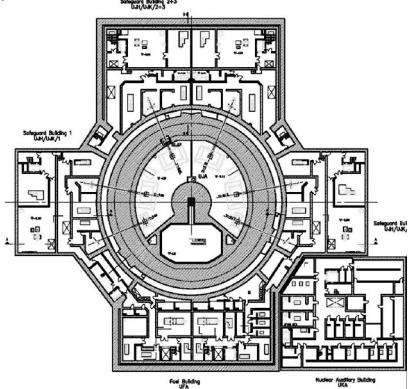
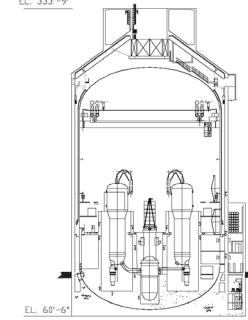
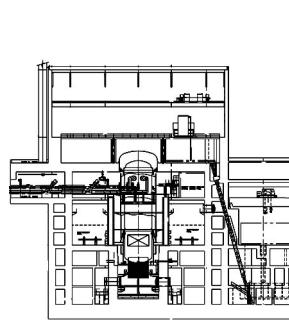


1970's PWR
1000 MWe
40 MT_{steel}/MW

Gen III - Active



Gen III+ - Passive



EPR
1600 MWe
49 MT_{steel}/MW

ABWR
1380 MWe
51 MT_{steel}/MW

ESBWR
1550 MWe
— MT_{steel}/MW

AP-1000
1090MWe
42 MT_{steel}/MW

Large light water reactors with passive safety features will be difficult to beat for commodity electricity generation

From the perspective of resource inputs, natural gas is the only fuel that can compete with nuclear energy

- Nuclear: 1970's vintage PWR, 90% capacity factor, 60 year life [1]
 - 40 MT steel / MW(average)
 - 190 m³ concrete / MW(average)
- Wind: 1990's vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]
 - 460 MT steel / MW (average)
 - 870 m³ concrete / MW(average)
- Coal: 78% capacity factor, 30 year life [2]
 - 98 MT steel / MW(average)
 - 160 m³ concrete / MW(average)
- Natural Gas Combined Cycle: 75% capacity factor, 30 year life [3]
 - 3.3 MT steel / MW(average)
 - 27 m³ concrete / MW(average)

Concrete + steel are >95% of construction inputs, and become more expensive in a carbon-constrained economy

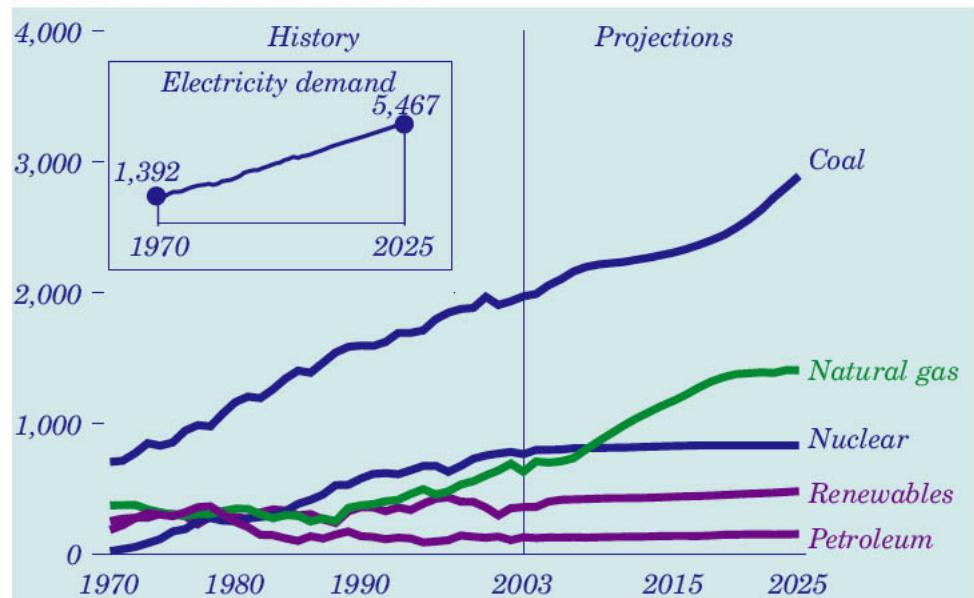
1. R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)
2. S. Pacca and A. Horvath, *Environ. Sci. Technol.*, **36**, 3194-3200 (2002).
3. P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," U. Wisconsin Report UW-FDM-1181, August, 2002.

DOE Energy Information Agency's electricity projections depend strongly upon assumed capital cost of nuclear power plants

- 2005 EIA Energy Outlook report
 - “Reference” case: \$1901/kW declining by 10% by 2025 - no new nuclear plants
 - “Advanced nuclear”: \$1818/kW declining 28% - 7 GW new nuclear plants by 2025
 - “Vendor estimate”: \$1604/kW declining 38% - 25 GW new nuclear plants by 2025
- General Electric statements (9/05) on fixed-price, turn-key bids
 - New ABWR's (nth-of-a-kind): \$1450 to \$1550/kW
 - New ESBWR's (1st-of-a-kind): approximately \$1350/kW

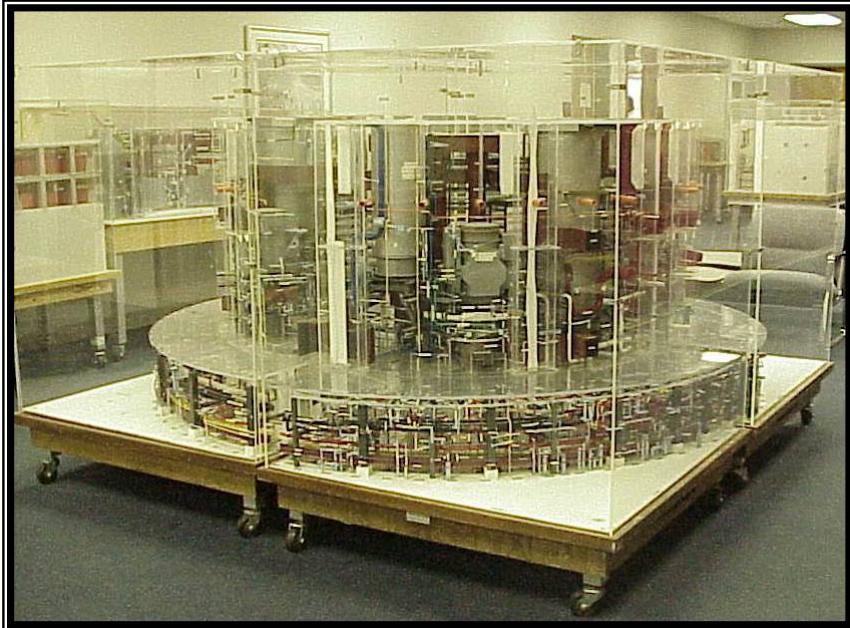
If General Electric's and Westinghouse's cost estimates prove correct, more new U.S. capacity built up to 2025 may be nuclear rather than coal or natural gas

Figure 5. Electricity generation by fuel, 1970-2025 (billion kilowatthours)



New nuclear infrastructure will be more highly optimized

1978: Plastic models on roll-around carts



McGuire Nuclear Station Reactor Building Models.

2002 NRC processing time for 20-year license renewal: ~18 months

2000: 4-D computer aided design and virtual walk-throughs

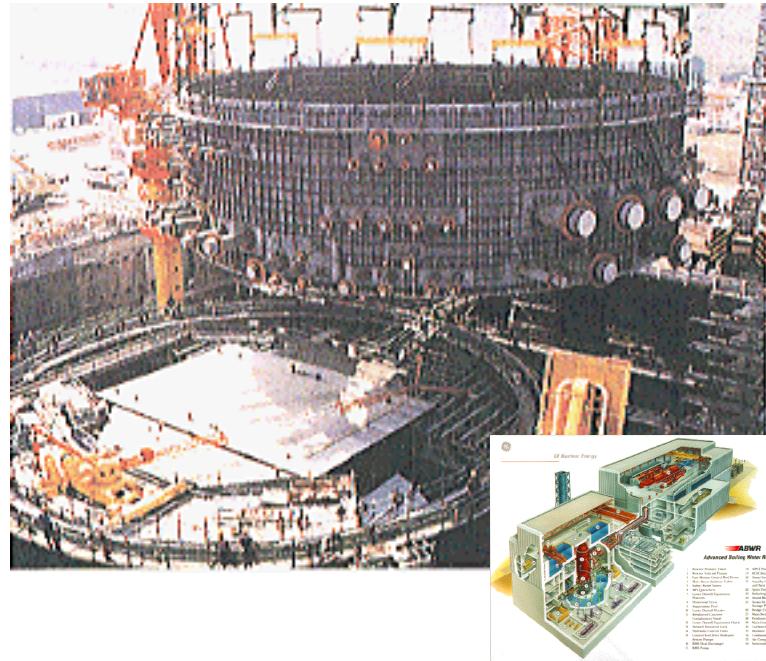


1000 MW Reactor (Lianyungang Unit 1)

“Modular” design no longer requires “cookie cutter” construction



Modern cruise-ship construction using 3-D computer aided design and automated manufacturing

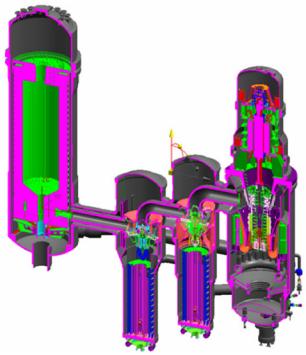


ABWR modular assembly reduced construction time to 52 months

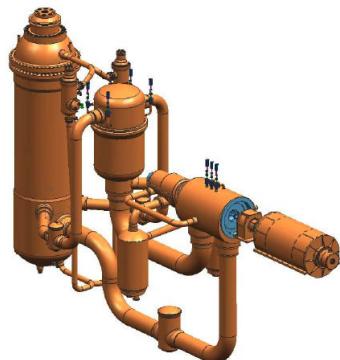
Where are the opportunities for large improvements in economics and safety performance?

- Low-pressure containment/confinement structures optimized for external events (natural and security related)
 - Gas-cooled reactors--vented confinements
 - Low volatility coolants
 - » liquid metals
 - » molten salts
- Long thermal time constant for reactor core heat up
 - Large thermal inertia from fuel and coolant
 - Large temperature margins to fuel damage
 - Elimination of complex and expensive active safety equipment
- Highly efficient, high power density energy conversion
 - High coolant temperatures
 - Compact closed gas cycles
 - Direct thermo-chemical production of hydrogen
- Flexibility to evolve rapidly
 - Risk-informed licensing
- Flexibility to evolve to provide alternate products
 - hydrogen production
 - actinide management

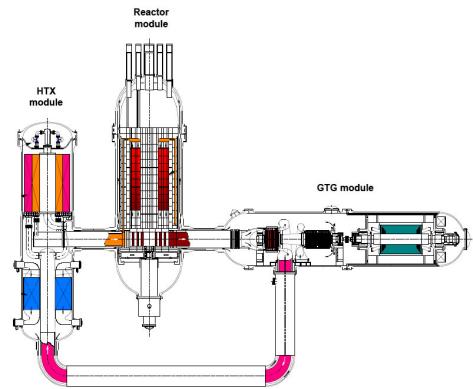
The transition to compact, high-efficiency gas Brayton cycles has key implications for Generation IV reactors



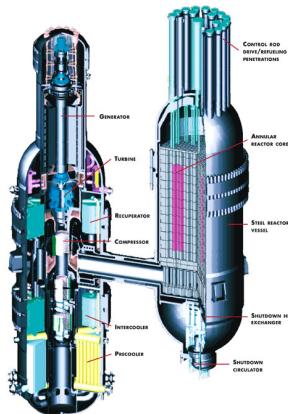
PBMR-Vertical
110 MWe



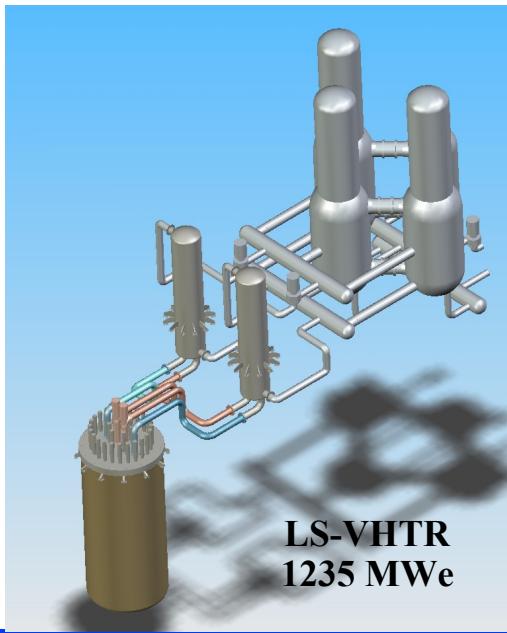
PBMR-Horizontal
165 MWe



HTR-300
274 MWe



GT-MHR
286 MWe



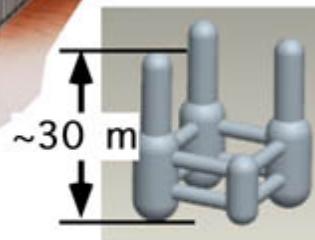
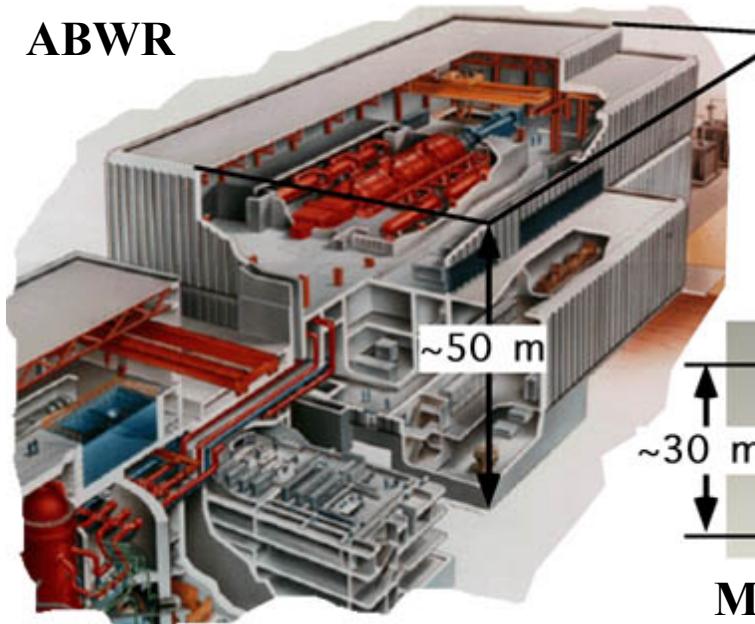
LS-VHTR
1235 MWe

General advantages:

- increased cycle efficiency (>45% compared to 33% for LWRs)
- reduced cooling water
- higher temp. heat rejection
 - dry cooling
 - desalination
- higher power density

A scaled comparison of the 1380 MWe ABWR turbine building and ~1300 MWe closed gas cycle equipment

ABWR

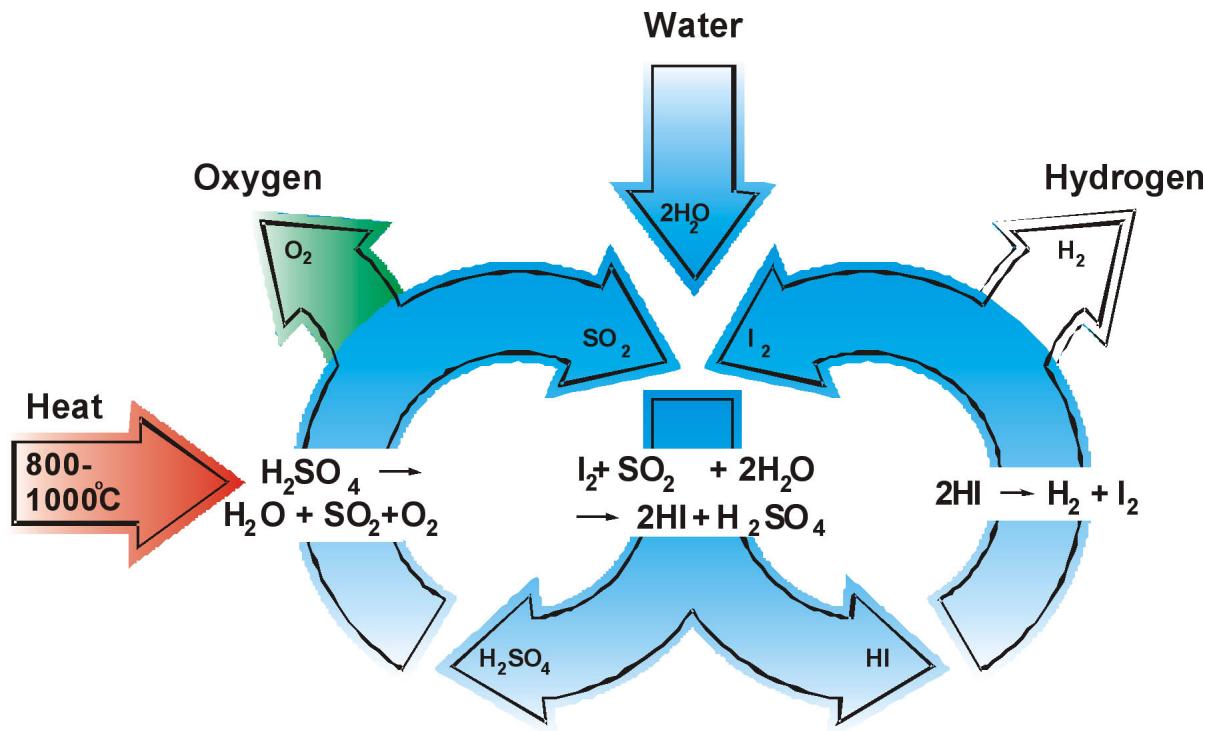


Multi-reheat
gas Brayton

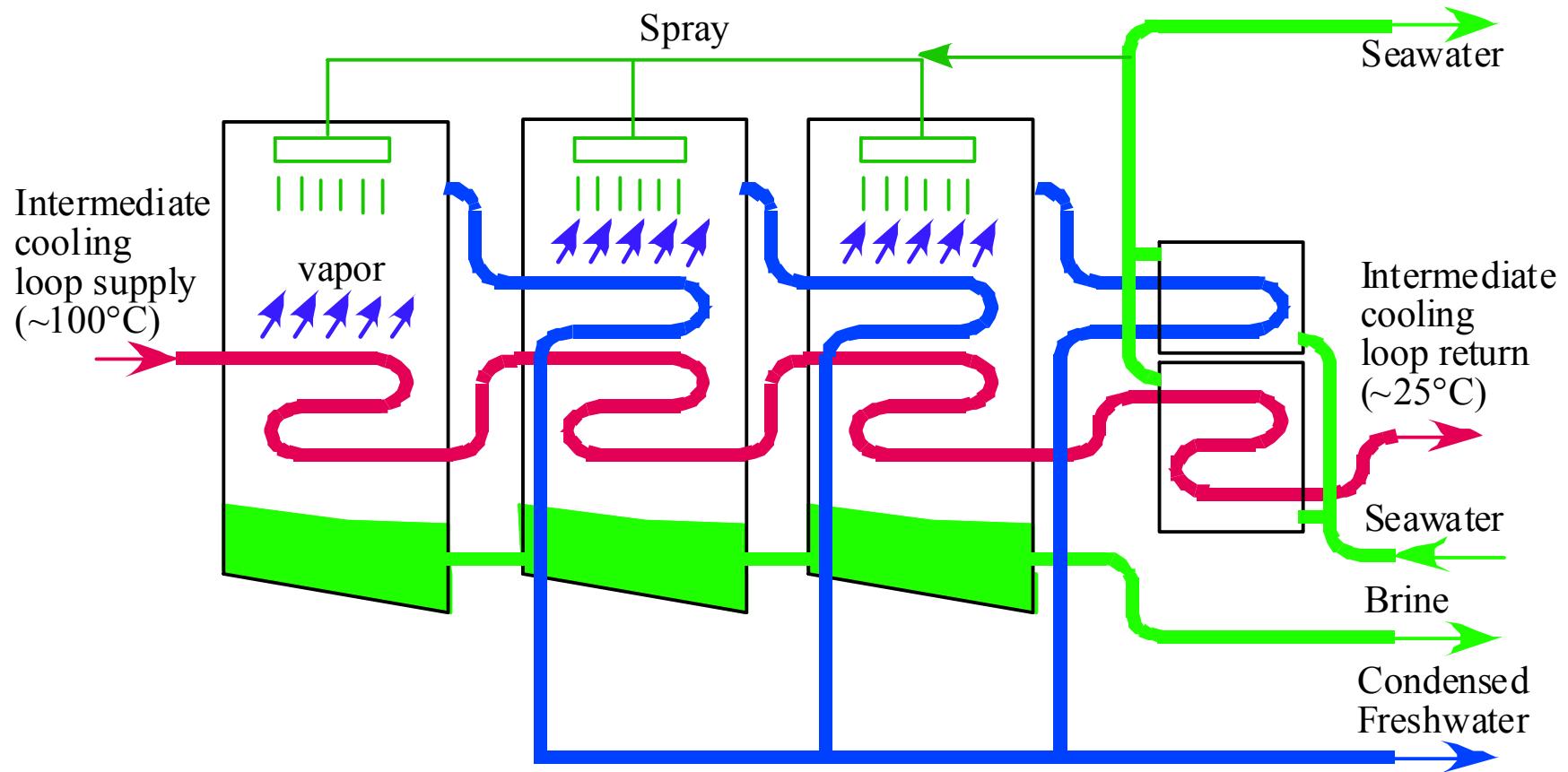
Closed gas power cycles can likely achieve a substantial reduction of the turbine building volume

- Gas cycle turbine building must also contain crane, turbine lay-down space, compressed gas storage, and cooling water circulation equipment
- Gas cycle requires ~1100 MWt of cooling water capacity, compared to 2800 MWt for ABWR

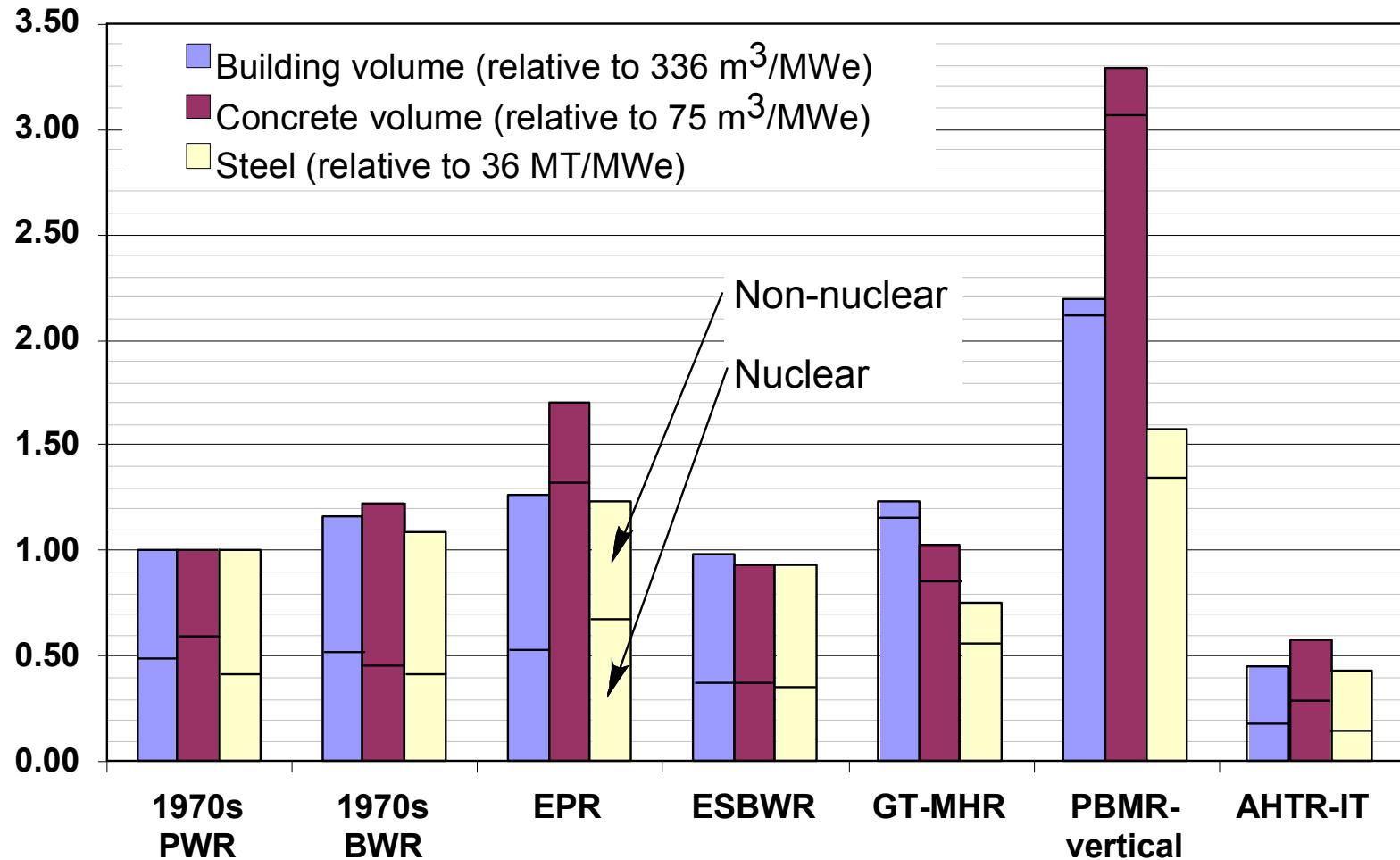
Alternative products: High temperature reactors can make hydrogen directly through thermo-chemical processes



Alternative products: High-temperature gas cycles can drive multi-effect distillation for desalination



Detailed comparison of building volume, concrete volume and steel consumption - can smaller reactors compete?



Simulation for Safety and Reliability

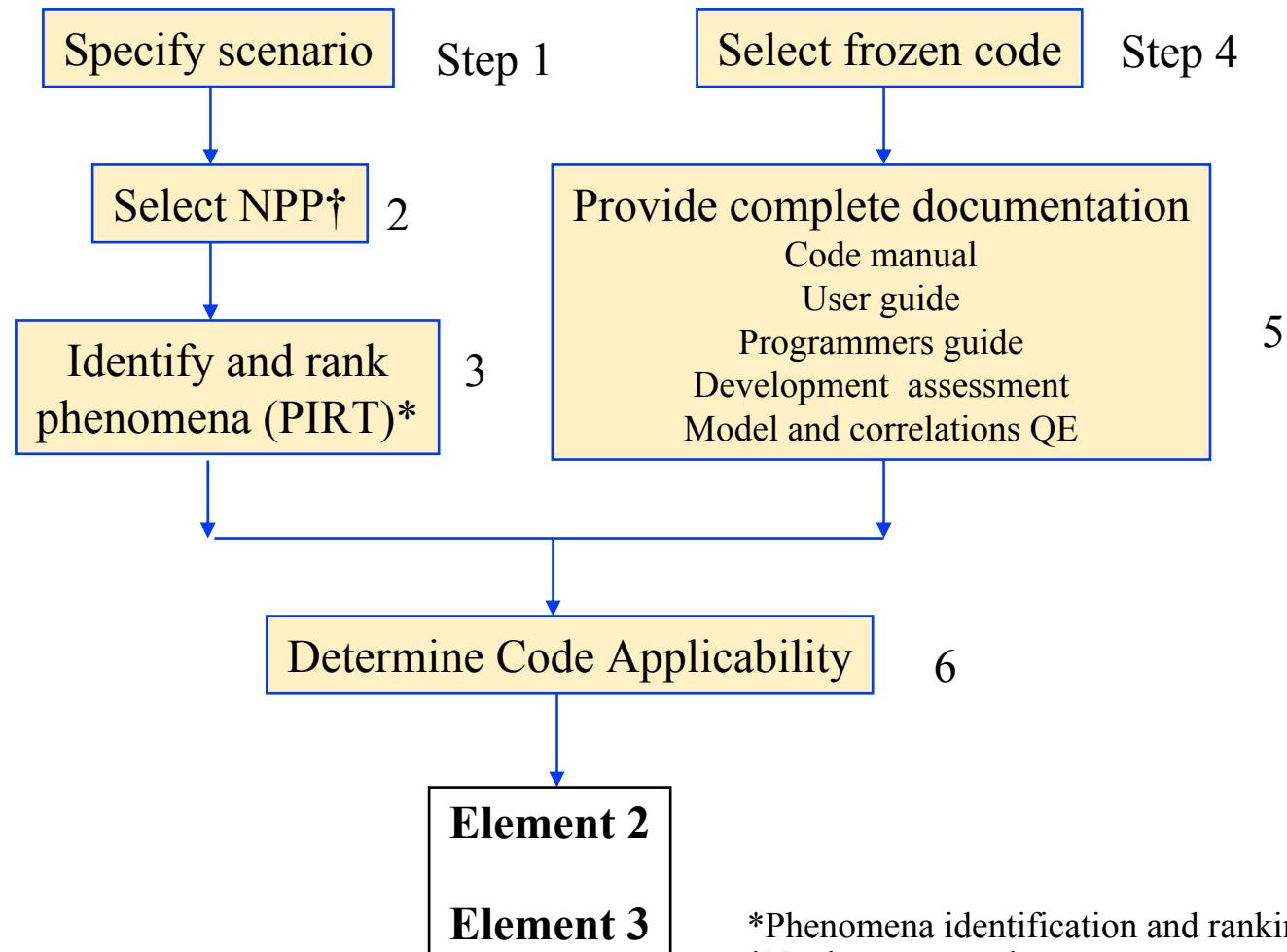
- Safety assessment requires understanding system response for operational transients and accidents (seconds to days)
 - Modern approach uses the Code Scaling, Applicability and Uncertainty Analysis (CSAU) methodology
 - Structured approach to identify:
 - » dominant system phenomena
 - » separate effects and integral experiment requirements
- Reliability requires prediction of materials and equipment performance over long time periods (years to decades)
 - Materials properties and equipment performance must remain inside bounds set by safety design requirements
 - » Assure through plant parameter monitoring and equipment surveillance and in-service inspection
 - Reliability is a major driver for investment risk
 - » Experience can take decades to accumulate, creates aversion to adopting new coolants, structural materials, and fuels



S. Levy, 1999

CSAU uses 14 steps for key phenomena identification, experimental validation, and uncertainty quantification

Element 1
Requirements
and code
capabilities



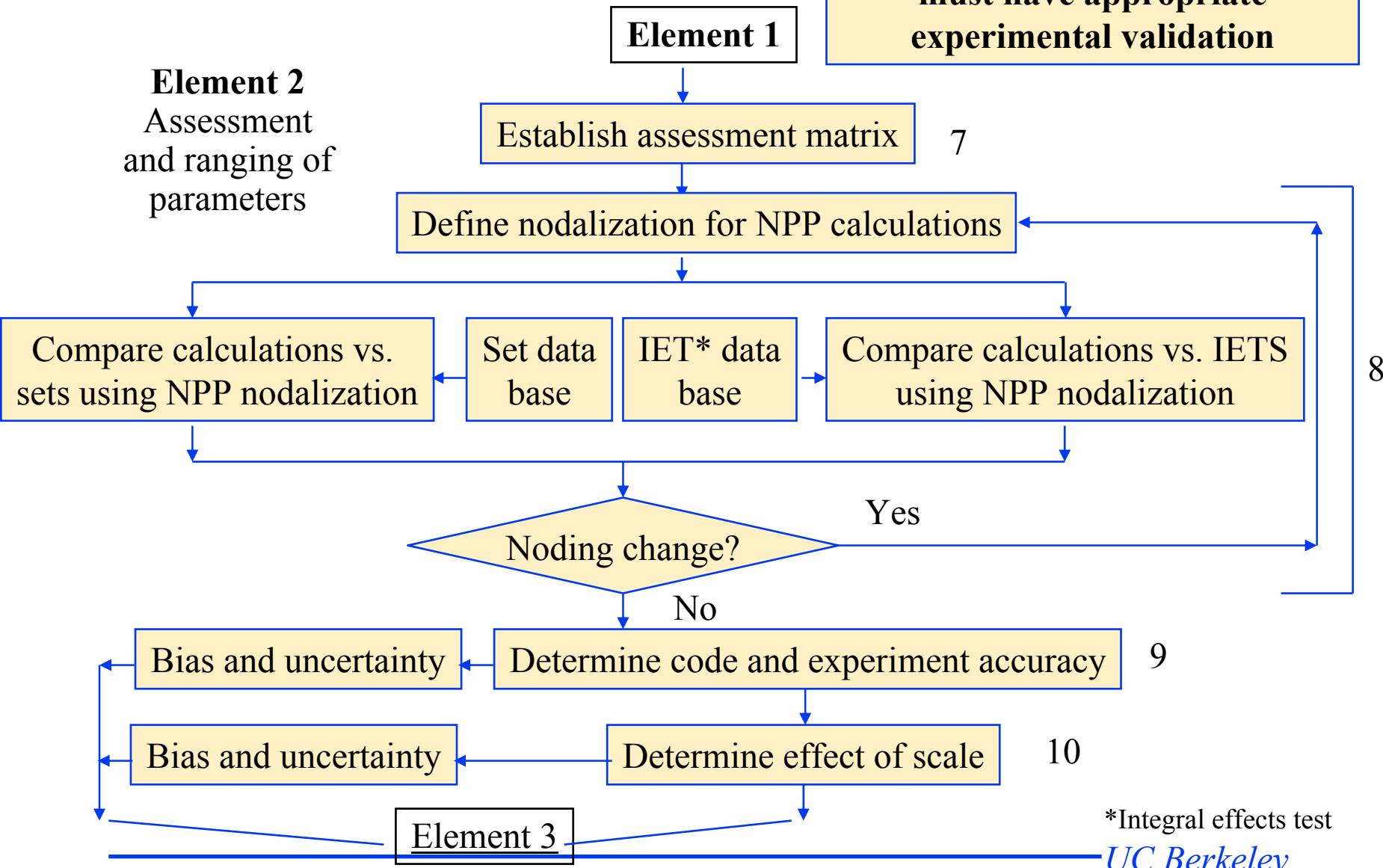
*Phenomena identification and ranking table
†Nuclear power plant

CSAU (continued)

To be useful for safety assessment, all simulation tools must have appropriate experimental validation

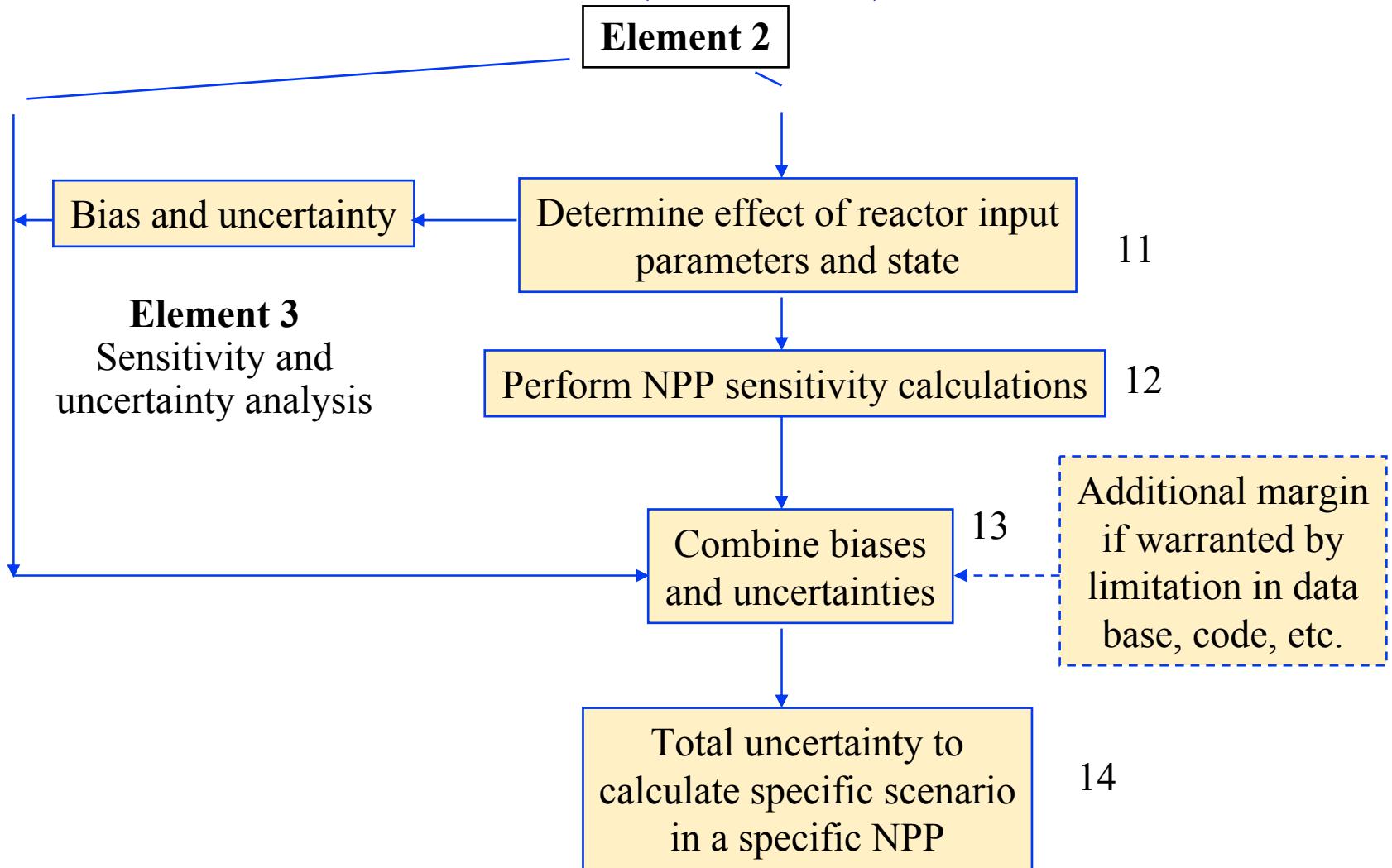
Element 2

Assessment and ranging of parameters



*Integral effects test
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CSAU (continued)



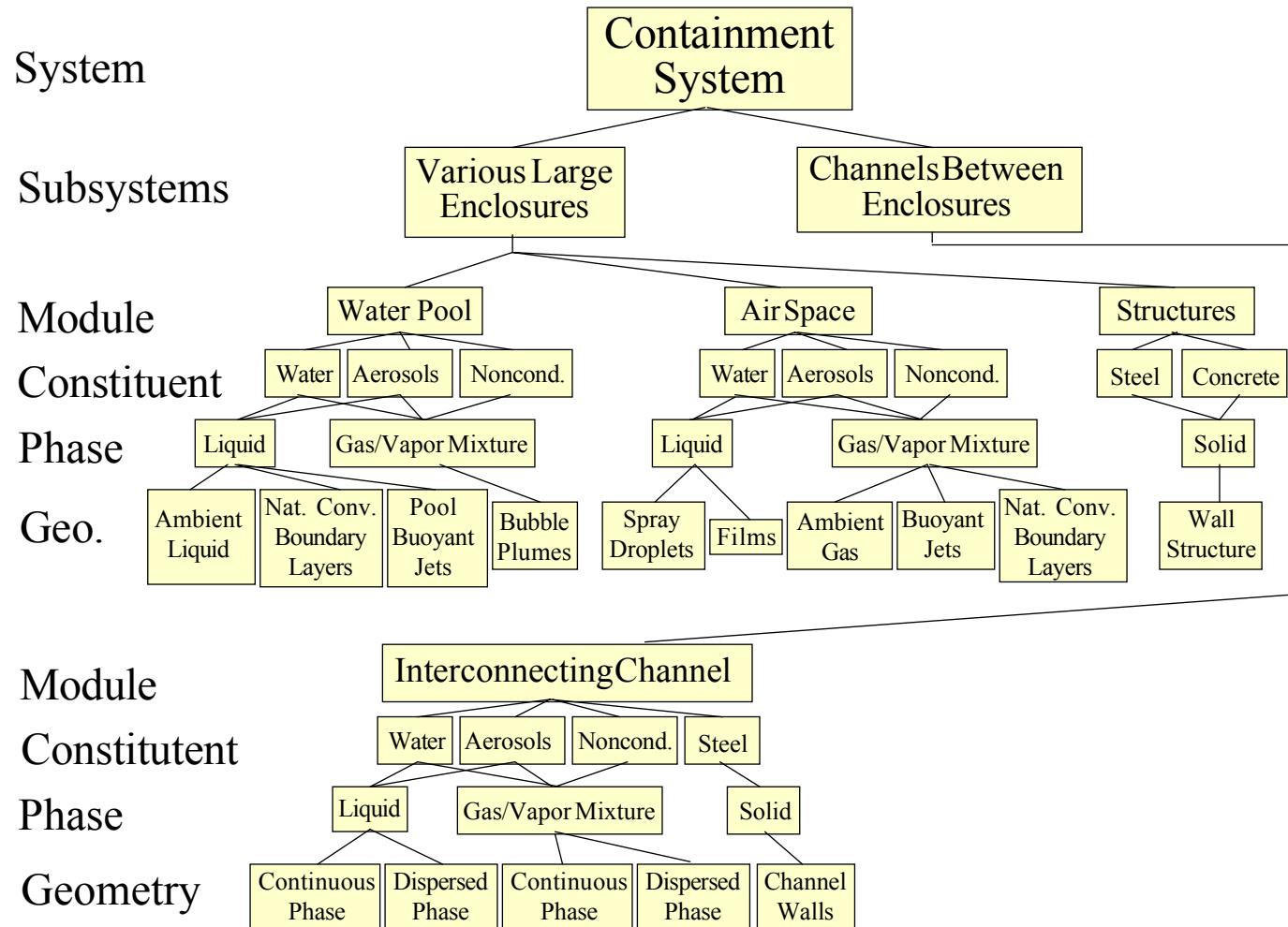
*Integral effects test

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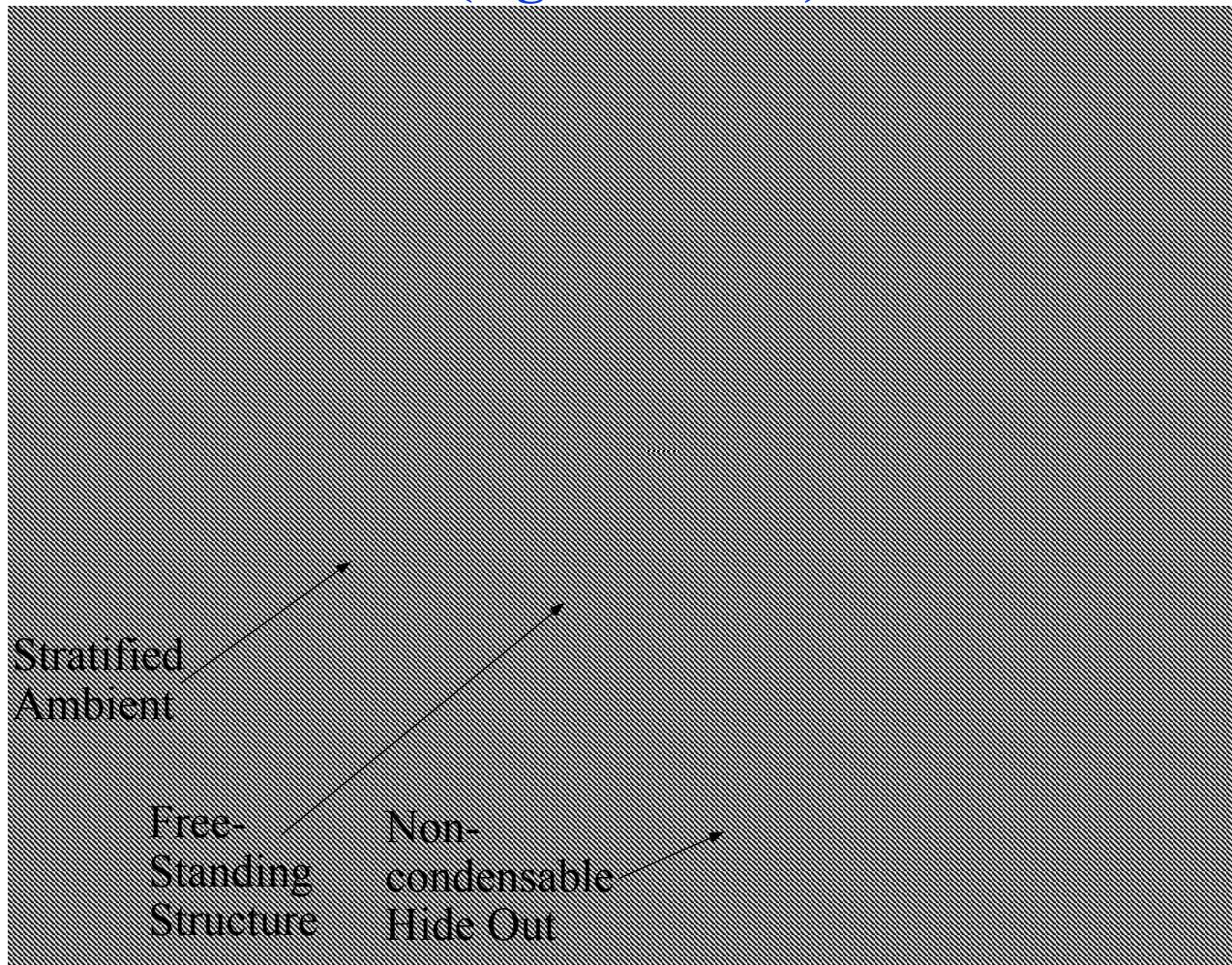
For safety-related simulation needs, the rubber hits the road with Phenomena Identification and Ranking Tables

- Identify NPP and scenario (e.g. initiating event)
- Disaggregate system and transient response into:
 - Spatial regions
 - » choose boundaries that give logical boundary conditions (e.g. LOCA fuel rods, core, upper plenum, hot leg, etc.)
 - Temporal phases
 - » Choose time phases where transitions in dominant phenomena occur (e.g. LOCA blowdown, refill, reflood)
- Systematically identify and rank phenomena that are important in each spatial region and temporal phase
- Define the experiments required to validate modeling tools
 - Scaled separate effects experiments
 - » boundary and initial conditions for a region and phase are imposed artificially to replicate a phenomena
 - Scaled integral effects experiments
 - » coupled phenomena for multiple regions and/or phases are generated in scaled experiments, or
 - » experiments are performed using a prototypical system

Example: Spatial regions for LWR containment mixing during LOCA and MSB accidents



1-D stratified/Zero-D well-mixed large enclosure model (e.g. AP-1000)



Phenomena time scales play a key role in scaling for large-volume mixing

- Residence time, τ_{bj} : ratio of the volume and flow rate

$$\tau_{bj}^s = \frac{n_{bj}V_{bj}}{Q_o} \quad \tau_{bl}^s = \frac{n_{bl}V_{bl}}{Q_o} \quad \tau_{sf} = \frac{V_{sf}}{Q_o}$$

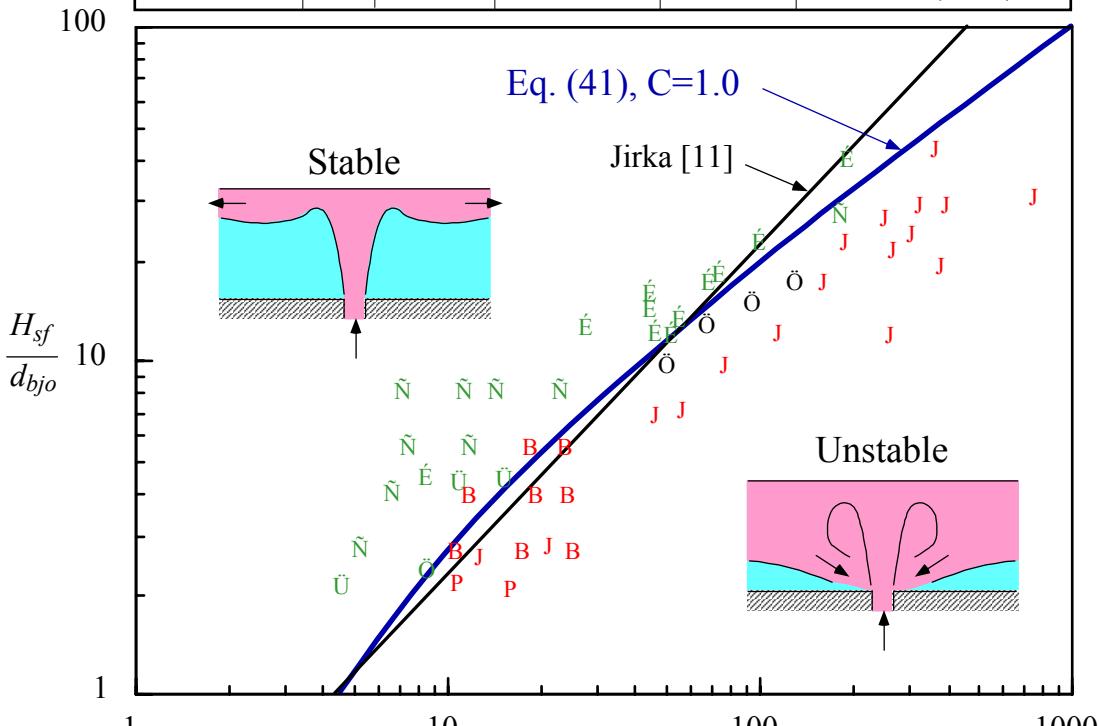
- Ambient fluid versus free and wall jets residence:

$$\frac{\tau_{sf}}{\tau_{bj}^s} = \frac{V_{sf}}{n_{bj}V_{bj}} \gg 1 \quad \frac{\tau_{sf}}{\tau_{bl}^s} = \frac{V_{sf}}{n_{bl}V_{bl}} \gg 1$$

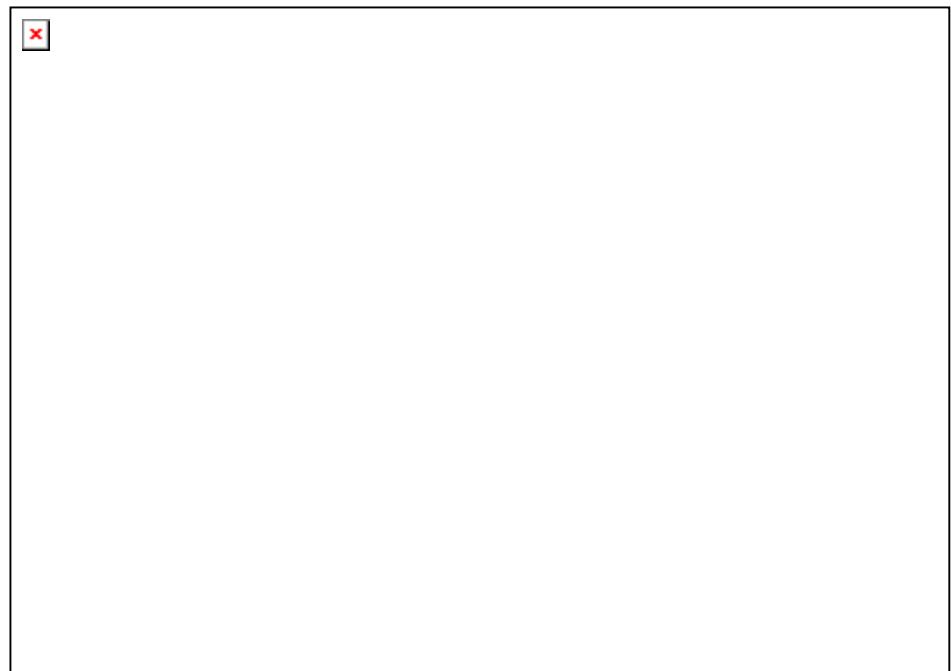
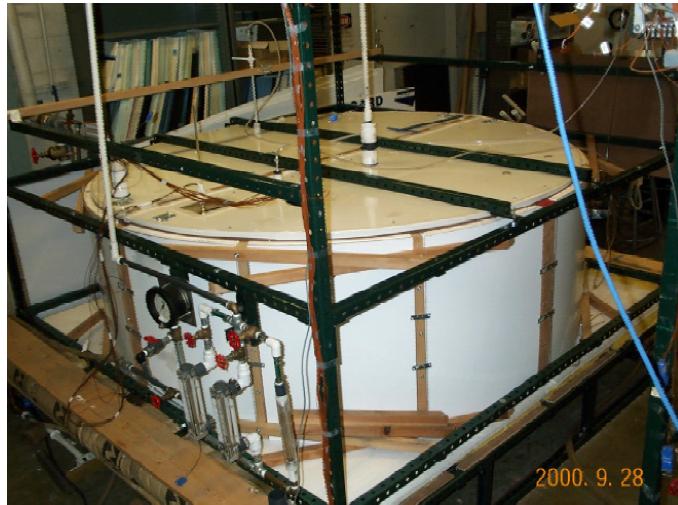
- If scale ratio is large, scaling rules say:
 - the jets transport mass and energy instantaneously within the ambient fluid,
 - the jet entrainment rate, trajectory and discharge location can be predicted using quasi-steady empirical correlations, without analysis of the detailed transient turbulent transport within the jets,
 - the volume occupied by the jets can be neglected, and the jets can be modeled as line or plane sources and sinks for mass, energy, and species.

Apply scaling to experimental data

θ		Stable	Submerged jump	Unstable	Source
Vertical	90°	É	Ö	J	Lee et al. (1974)
Near-Horizontal	20°	Ü		P	Jain and Balasubramanian (1978)
	0°	Ñ		B	



Experiments are central to validating simulation model physics



Reactor designers have strong incentives to reduce the complexity of system transient response

- **Simplicity reduces R&D costs and speeds regulatory review**
- **Reduced complexity comes from design strategies that simplify**
 - **Boundary conditions between regions**
 - » **Impermeable, rigid boundaries**
 - » **Boundaries separating regions with dominant phenomena with greatly different characteristic time scales**
 - Small area channels between large volumes
 - Turbulent fluids transferring heat to high inertia solid structures (channel flows)
 - In general, cases where slow phenomena responds only to the time-integrated effects of fast phenomena
 - **Initial conditions for subsequent phases**
 - » **Later phases have much longer time scales than early phases**
 - In general, all cases where core and coolant have long thermal response times compared to accident initiating phenomena
 - **Integral experiment scaling**
 - » **Decay heat removal system modularity (as opposed to surface-area to volume scaling) (also simplifies separate effects and component testing)**
 - » **Low distortion under reduced height/reduced area/simulant fluid scaling**
 - **Reactivity control may couple with important phenomena (e.g. fast reactors)**

When reactors are designed to minimize the complexity of transient response, residual uncertainty comes primarily from long-time-constant phenomena

- Uncertainty in materials properties/equipment performance due to long-term radiation/thermal/chemical/mechanical effects
 - solid materials thermophysical properties (particularly thermal conductivity, component dimensional changes)
 - surface emissivity
 - corrosion-cracking/erosion/galling/fouling
 - fuel isotopic composition and decay heat generation
 - chemical reaction, melting and vaporization
- Strategies for reducing uncertainty
 - Experimental
 - » materials testing in prototypical chemical and thermal environments
 - » test reactor irradiation
 - » component reliability testing (the Admiral's test)
 - Modeling and simulation--improved methods and physics
 - Operational (create potential for reduced capacity factors)
 - » monitoring, surveillance and in-service inspection

Conclusions

- **Modeling and simulation are key ingredients to achieving goals for new reactor design**
 - Economics, PR&PP, sustainability, and safety and reliability
- **Reactor designers will have strong incentives to find new modeling tools and adopt design strategies that reduce the complexity/uncertainty of transient analysis**
 - Integral effects experiments are required for licensing and can be expensive and time consuming for some design approaches
 - For optimal designs, focus will be on reducing uncertainty from phenomena
 - » that evolve over long time periods (reliability and capacity factor)
 - » that limit power up-rates (safety)
- **Many simulation needs will be reactor-concept specific**
 - Phenomena identification and ranking tables provide a key tool to identify simulation needs
 - Close interactions between modelers and reactor designers is required so correct phenomena are focused on
- **Other modeling capabilities will also be important**
 - FEM modeling of thermal/mechanical/seismic response, etc.